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Advances in mathematical modelling of postharvest refrigeration processes

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Abstract
Purpose of review: This review summarises advances in the application of mathematical models for predicting and optimising fluid flow, heat and mass transfer and associated phenomena during postharvest refrigeration of horticultural products.
Findings: There has been an interest in the use of mathematical models for optimising postharvest refrigeration systems operation and design. These mathematical models are applied to predict the physical and chemical phenomena that take place during postharvest handling of horticultural products. Nowadays, with the availability of more powerful computers at a reasonable price, it is feasible to investigate the details of the flow behaviour in large-scale refrigeration systems at a very small spatial and temporal scale.
Directions for future research: In most of the recent models, the stored product along with the container was assumed as a porous medium. With this assumption, it is not possible to predict the detailed flow behaviour through the container and around each product in the container. To date the turbulence dynamics in the stack has not been properly investigated. In order to improve the accuracy of the models, models that include the detailed geometry of the stacked product and the container, and the use of better turbulence models will be very important. To better understand the phenomena at all levels of the refrigeration process, a multiscale modelling approach is required.

Keywords: horticultural product; refrigeration; mathematical model; CFD; storage; fruit

Abbreviations

CA	Controlled Atmosphere
CFD	Computational Fluid Dynamics
DE	Discrete Element
LBM	Lattice Boltzmann Method
MA	Modified Atmosphere
MAP	Modified Atmosphere Packaging
PIV	Particle Image Velocimetry
RNG	Renormalisation Group
ULO	Ultra Low Oxygen

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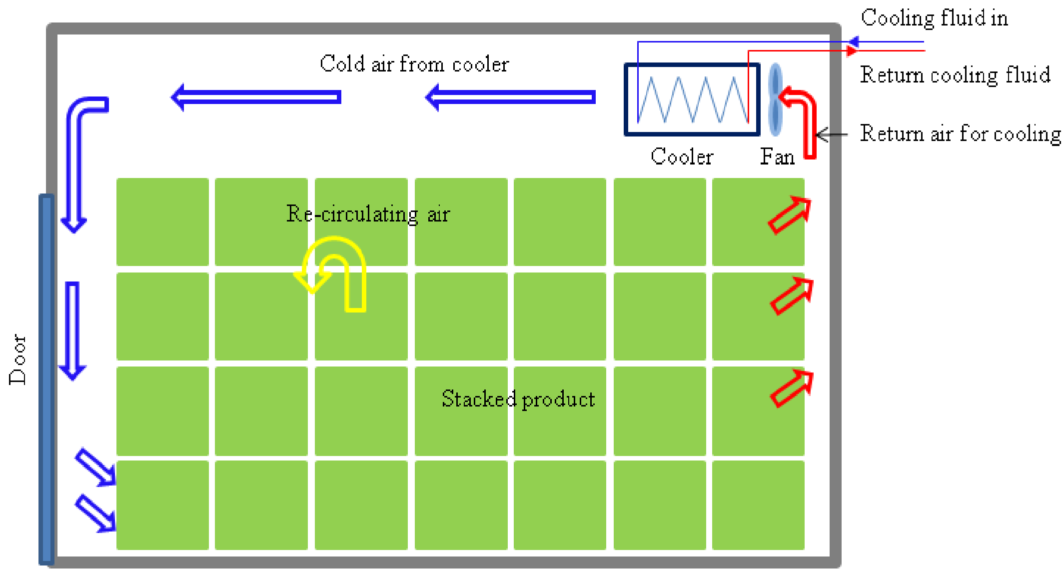
Introduction
Refrigerated storage systems are mostly used to preserve the quality of horticultural products by minimising respiratory heat generation, retarding the ripening process, and preventing moisture loss and microbial spoilage [1*, 2]. Different methods of cooling are available, these include: room cooling, forced-air cooling, vacuum cooling, hydro cooling and package icing. Due to its flexibility, efficiency and low cost, forced-air cooling is the most commonly used method [3]. Forced-air systems commonly consist of a cooling unit assembly with cooling coils in which the refrigerant is circulated and a fan that forces cooling air over the coils and on to the stacked product (Figure 1). The cooling units can be a direct one where the refrigerant evaporation takes place in the cold room or an indirect one where a secondary fluid cools the air.

Horticultural products can be handled either in large bulks or placed inside larger or smaller containers or packages. These containers or packages usually have vents that allow for flow of the cooling air to the produce. The cooling effi-

Figure 1. Typical forced-air cooling system of horticultural products.



ciency depends on the flow resistance that is induced by the container and the product. Non-homogeneous flow of the cooling air inside the stack may cause uneven cooling and affect product quality [1*, 8–10*, 11]. Generally the transport phenomena (airflow, heat and mass transfer) during cooling of horticultural products are complex; mathematical models are recommended to better understand and design refrigerated storage systems [1*, 11, 12*, 13*].

Mathematical models are being used extensively in many areas to analyse or improve an existing process and design, and to develop new designs. Modelling techniques are gaining interest as an alternative to expensive and difficult experiments because computers continuously become more powerful and less expensive, software is readily available, and once a model is validated it is a versatile tool for evaluating the effects of the operating and design parameters involved. In the agro-food area, mathematical models are being used to optimise and develop equipment and operational strategies, and their use has grown exponentially over the last decade [1*–10*, 11, 12*, 13*–22*, 23–31*, 32–50*, 51] (Figure 2).

Different modelling approaches have been proposed for predicting fluid flow, heat and mass transfer during cooling, storage, transportation and display of horticultural products. Three categories can be distinguished. The first approach is computational fluid dynamics (CFD) where the appropriate geometry is discretised and the governing partial differential equations (Navier–Stokes equations) for conservation of mass, momentum and energy are solved [1*–3, 13*, 14, 20–31*] on a discrete mesh on the geometry and using a numerical method such as the finite volume method or the finite element method. The second approach is the zonal method where the system is assumed to be a set of well mixed zones of homogeneous composition [15–17], and where simplified ordinary differential equations are used to describe mass and energy exchanges between zones. Finally, the third approach uses a relatively new class of computational techniques, namely the lattice Boltzmann method (LBM). In this model, instead of solving the macroscopic Navier–Stokes equations a certain volume of fluid is represented by a collection of fictive particles; during motion particles can collide on a regular lattice obeying the fundamental conservation laws [18–19, 34]. LBM uses simplified kinetic models that incorporate the essential physics of microscopic processes so that the macroscopic averaged properties obey the desired macroscopic equations [34]. Although it is a powerful technique for studying complex flows, computationally LBM is very demanding. For modelling the refrigeration process of horticultural products, due to its low computational power requirement and reasonable accuracy of the models, the traditional CFD approach is the primary methodology of choice [12*]; for example, the result from CFD modelling of the cold storage humidification system is presented in Figure 3.

Previously, Smale *et al.* [12], Norton and Sun [14], Xia and Sun [32], and Wang and Sun [33] presented a comprehensive review of CFD modelling in agro-food applications. This paper focuses on the more recent mathematical modelling studies of different postharvest refrigerated system applications, including chillers, cold stores, refrigerated vehicles, display cabinets, domestic refrigerators and some emerging applications. New trends and directions for future research are presented. To conclude the paper, some final remarks are made.

Figure 2. Number of papers published: ○ category food/fruit/vegetable and mathematical model; □ subcategory cooling/refrigeration/storage (source: ISI web of knowledge).

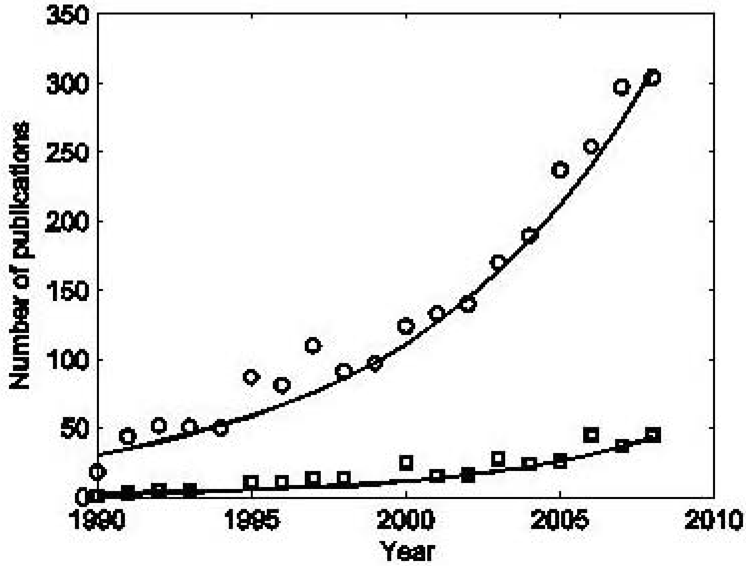
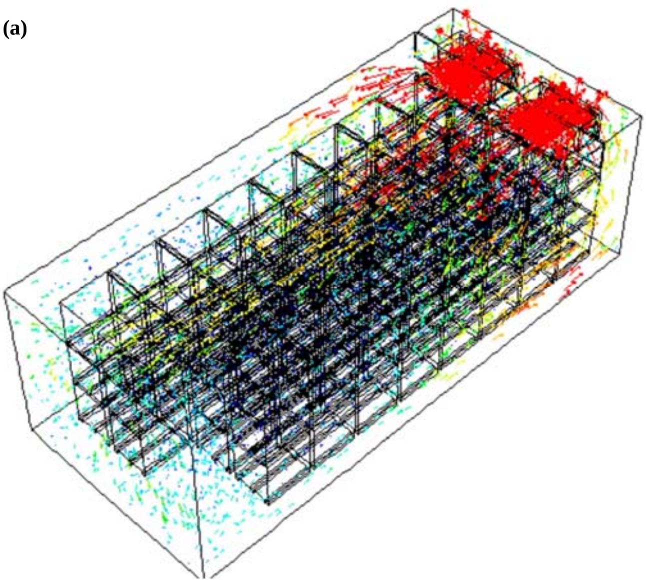
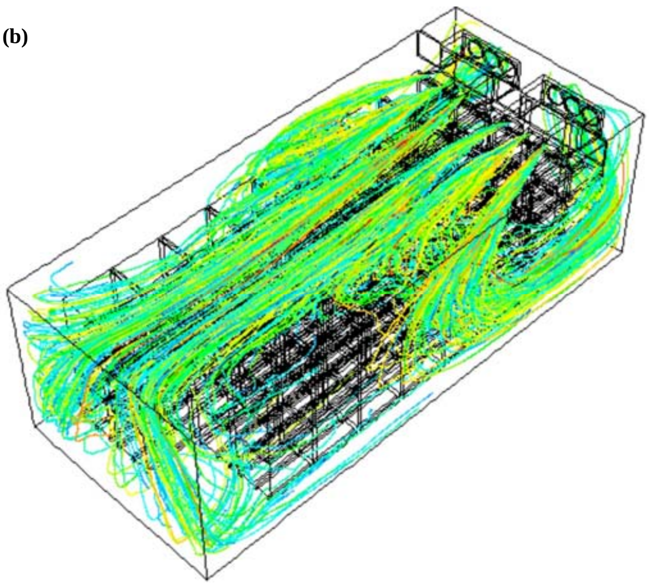


Figure 3. Air velocity vectors (a) and tracks of sprayed droplets injected from six humidifying nozzles (b) for loaded chicory root cold storage room; velocity vector: 2 m/s (red), 0 m/s (blue); droplet diameter: 18.5 µm (red), 2.5 µm (blue) [48].

(a)



(b)



Model application in postharvest refrigeration areas

Chillers

Chillers are mostly used to remove the field heat from harvested horticultural products; this helps to slow down the physiological activity and deterioration before long/short term cold storage, display or transportation. Cuesta and Lamúa [35] developed an analytical Fourier series solution to the equation for heat transfer by conduction in simple geometries with an internal heat source linearly dependent on temperature that was applied to the chilling of horticultural products.

However, for products with irregular shape and temperature dependent thermo-physical properties it is not possible to get such an exact analytical solution; in such cases the use of numerical methods is mandatory [36]. By using a macro-porous medium approach, Alvarez and Flick [11] developed a validated two-dimensional model that predicted turbulence, velocity, pressure, local heat transfer coefficient and product temperature during forced-air cooling of stacks of food products. This model included the dissipation and generation of turbulence in the porous medium that was not considered in most relevant studies [13*, 20–22*, 23, 27, 28]. Alvarez and Flick [9] observed turbulence generation behind the stacked product and later Alvarez *et al.* [10*] proposed a one equation semi-empirical model for two-dimensional turbulence flow through a porous medium that took into account this turbulence generation. It was reported that this free stream turbulence inside the porous medium has a major effect on transfer phenomena.

For design of hydrocoolers for horticultural products, Thorpe [38] used a semi-continuum approach that treated the individual horticultural product as discrete particles; their averaged properties, along with those of the cooling water and interstitial air, were treated as continuum. To determine the cooling efficiency, the study stressed the importance of using the mass weighted average temperature instead of the core temperature of the produce. The model was used to study effects of cooling water flow rate and temperature, and size and depth of the bed of the produce on cooling rate.

Zorrilla and Rubiolo [39] developed a mathematical model for immersion chilling of solid foods. Three phases were considered, the rigid solid matrix, the liquid phase and the ice phase. Transport equations for continuous medium were applied to each phase. The solid matrix was treated as a porous medium. The model was capable of predicting solute uptake and temperature of the product. Though the importance of vacuum cooling of horticultural products was thoroughly discussed, most of the papers on mathematical modelling of vacuum cooling mainly address cooling of meat products [40].

Cool stores

Nahor *et al.* [13*] developed a two-phase momentum, heat and mass transfer CFD model of an empty and loaded air cooled cold storage room. The product used in this study was pear, *Pyrus communis* cv. Conference. The model was able to predict the cooling airflow, the air and product temperatures and product moisture loss as a function of position in the cool store. Agreement of the simulation and measured results was good. The model was capable of predicting the cooling rate of the air and the produce. However, some discrepancies in the temperature were observed; this was caused by the under-prediction of the airflow velocity. The standard *k-e* turbulence model that was used to model the turbulence, the assumption of uniform initial temperature inside the bin and neglecting the gradient inside the individual products were reported as the possible causes of this under-prediction.

Chourasia and Goswami [21] developed a model that predicted the airflow, temperature and moisture loss in a commercial potato cold store. The model considered the bulk of potato as porous medium and the RNG (Renormalisation group) *k-e* turbulence model was used. The model was in good agreement with measured results. With the model it was possible to locate the hot and cold spots inside the storage room, and the regions with poor air circulation where the relative humidity was about 7% lower compared than of the surrounding air.

Xie *et al.* [41] used a CFD model to study design parameters of cold stores. The model was used to evaluate the effects of storage corner baffles and product stacks on airflow and temperature fields. The model used uniform boundary conditions and source terms, *k-e* turbulence models with wall functions, geometrical approximations, and a relatively coarse grid that made the model simpler but limited the quantitative accuracy of the model.

Foster *et al.* [24] applied a validated three-dimensional CFD model to investigate air curtains that are used to restrict cold room infiltration. The model was used to evaluate effectiveness of air curtains at different air velocities. Using the model, it was possible to get a curtain setup with an effectiveness of 0.71 compared with the original 0.31. The result also showed that flow of air curtains cannot be considered two dimensional. The infiltration of air through doorways of cold storage rooms was also modelled by Foster *et al.* [42]. The model was validated with experimental results. The study showed the superiority of mathematical models over the commonly used analytical models to predict the airflow through large doors as the temperature both inside and outside varies with time and space.

Refrigerated vehicles

Using a CFD model, Moureh and Flick [22*] predicted the airflow and temperature profiles in a typical refrigerated truck loaded with pallets. In this case, the accuracy of the Reynolds stress turbulence model (which models individual components of the stresses in turbulent flow) was better than the two equation turbulence models (which only model the average properties of turbulence in the flow). The model was used to evaluate systems with and without air ducts (both configurations are extensively used in refrigerated transport) based on ventilation and temperature uniformity. The result showed that ventilation to the rear side of the truck and temperature uniformity was improved by using the system with air ducts. The model was also used to study turbulence characteristics, and effects of the pallet and its confinement on flow phenomena.

Recently, Moureh *et al.* [23] used mathematical modelling to study air velocity characteristics within vented pallets loaded in a refrigerated vehicle with and without air ducts. In this model, the loaded vented pallets were taken as a porous medium where the pressure loss coefficients were determined in a separate wind tunnel experiment. Since there was a large difference between the pallet dimension and the small gaps between them, direct meshing of this small gap leads to a large number of meshes that is computationally very demanding. To avoid this difficulty, an approach that was proposed by Tapsoba *et al.* [43] was applied. In this approach, this small gap was replaced by a fictitious porous medium that gave the same airflow resistance to the actual gap. Based on this assumption the equivalent permeability of the fictitious porous gap was calculated. There was a reasonable agreement between predicted and measured results.

Display cabinets
CFD-aided design of an air curtain display cabinet was reported by Cortella [25]. This two-dimensional model was used to predict the airflow and temperature distributions of both horizontal and vertical display cabinets. The model was used to investigate the external air infiltration and power consumption. Due to lower entrainment of warm air from the outside, the horizontal cabinet was found to be more energy efficient and effective. The performance of the cabinets was highly dependent on the velocity of the refrigerated air; it was not possible to get the required cooling when the velocity was too low and too high air velocity created strong turbulence that increased the heat and mass transfer rate. The model was also proposed for studying effects of air curtain temperature, cabinet geometry and loading pattern.

D'Agaro *et al.* [26] developed two- and three-dimensional models of a vertical display cabinet that predicted the airflow pattern and temperature distribution. The model used a *k-e* turbulence model. Due to their lower accuracy, two-dimensional models for such display cabinets were not sufficient. Because they predicted the airflow and temperature with better accuracy, the three-dimensional models were recommended.

Domestic refrigerators
To study the airflow due to natural convection inside a domestic refrigerator, Amara *et al.* [44] developed a three-dimensional CFD model and validated it with experimental measurements. The measurements were performed using particle image velocimetry (PIV). The agreement between measured and predicted results was relatively good. The influences of cold wall temperature and dimensions of the cold wall were studied. Based on this study, consumers are advised to put the product at least 2.5 cm from the walls of the refrigerator to avoid the blockage of the air circulation. Laguerre and Flick [45] presented combined deterministic and stochastic approaches to predict the air and load temperature in a static domestic refrigerator. In this model, in addition to convection, radiation heat transfer was taken into account. The model took the room and thermostat temperature as random variables. The paper recommended the application of this methodology for other refrigerated systems such as cold stores, display cabinets and refrigerated vehicles.

Emerging applications

Products and packages
Package design is a prime concern for efficient cooling and proper cool storage. A larger vent area increases the cooling efficiency, but the strength of the package should be taken into account. Vingeault and Goyette [4] studied pressure loss through vented plastic boxes and a vent hole ratio ($O=A_{hole}/A_{box}$, where A_{hole} is the vent hole area and A_{box} is box face area) of 25–27% was recommended. Different modelling approaches have been used for packages. For predicting the airflow resistance through spherical products stacked in vented horticultural packages, van der Sman [5] developed an equation that expressed the total pressure drop as sum of the pressure drop of the bulk and the package. The pressure drop of the package was expressed as a function of the package vent hole ratio, and it was proportional to $O^{-1.5}$. However, the pressure drop can also be affected by other factors other than the vent hole ratio; the general use of a single formula may be questionable [1*, 6]. Later, Smale [6] developed an analytical equation of the pressure drop that includes the entrance, internal, exit and product space losses, based on experimental trials.

To study the flow through the bulk and loaded vented box, Delele *et al.* [7] developed a combined discrete element (DE)-CFD model. In this model, the DE method was used to generate a random stack of discrete spheres and the CFD was applied to study explicitly the airflow through the bulk and loaded vented box. The result showed the inhomogeneous flow distribution inside the stack. The model was used to study the effects of confinement ratio, flow direction, stacking pattern, product size, porosity, vent hole ratio and randomness of the filling. For flow through a vented box with products, a linear addition of the individual pressure drops of the flow through the box and the bulk by considering as series of resistances was shown to seriously underestimate the real pressure drop.

For direct modelling forced air cooling of packed strawberry, Ferrua and Singh [30] incorporated into CFD simulations the three-dimensional shape of the strawberry that was generated by combining digital images of its slices. The airflow distribution was validated by using PIV [31*]. Measurements were done using transport spheres that had an equivalent diameter to the strawberry. The geometric proportions, porosity, headspace dimension and venting design of the package were reproduced. In this model, the randomness of packed strawberries was not taken into consideration; however, it was reported that it has an effect on cooling air velocity distribution inside the stack but not on the pressure drop [7].

To investigate the airflow and heat transfer in ventilated packaging for horticultural products, Zou *et al.* [46] developed a CFD and later validated it with measured results [47]. The study was done for both in bulk and layered packaging systems based on a porous medium approach. The area inside the packaging was divided into three regions, namely the solid region (the package surfaces), the plain air region (package vent region) and the produce-air region. Tanner *et al.* [15–17] developed and tested a zonal model for the design of horticultural food packages for refrigerated systems. The model was used to study heat and mass flow phenomena.

Misting systems

The humidity level of a storage room can be controlled by using artificial misting systems. The advantages of such misting systems on decreasing saleable weight loss and maintaining the product quality during storage and handling has been thoroughly discussed in literature; however, there have been only limited studies on mathematical modelling for design of misting systems.

Allais *et al.* [37] modelled the heating kinetics of a stack of spheres during mist chilling. The model was based on a heat and mass balance of the air and spheres, taking into account local air temperature, local droplet concentration, heat and mass transfer coefficients. The simulated results were in good agreement with experimental results. The use of such two-phase flow system for cooling reduced the half cooling time by 30% relative to the single phase flow method. The paper reported the effects of air velocity, water mass flux density and air temperature on cooling kinetics.

Delele *et al.* [27] used multiscale CFD modelling to study a high pressure nozzle cold storage humidification system. At the smallest scale, the flow through stacked products in boxes was predicted using a direct DE-CFD modelling [7]; from this the anisotropic pressure loss coefficients were determined. At larger scale, a loaded cool room model predicted the airflow, temperature, humidity and fate of the fogged water droplets. To track the path and evaporation of the fogged droplets a Lagrangian particle tracking multiphase flow model was used. The loaded product was treated as a porous medium taking into account the information from the lowest scale. Using the model it was possible to quantify the amount of droplets that were completely evaporated and the amount of non-evaporated droplets that were deposited on the product and other room surfaces. The amount of deposition was affect by the position and direction of the humidifying nozzles. The agreement between measured and predicted results was good. Later, Delele *et al.* [48] applied the above model to evaluate a humidification system of chicory root cold storage room. The efficiency of the humidification system was affected by length of cold air deflector, stack height, number of nozzles and duration of humidification.

Gas circulation

During postharvest handling and storage of horticultural products, modified atmosphere (MA), controlled atmosphere (CA) or ultra low oxygen (ULO) is commonly used to complement the refrigerated storage. To study the gas exchange during bulk storage of pome fruit, Nahor *et al.* [49] applied a Michaelis-Menten type gas exchange model and found a good agreement between measured and predicted results. It was found that the age of the fruit influenced the gas exchange rate significantly and proposed that the kinetic parameters of the model be expressed as a function of the physiological age of the fruit to include the influence of age when the models are to be used to simulate gas exchange of bulk stored fruit for a longer storage period. Rennie and Tavoularis [50*] developed a general mathematical model that could predict the dynamic behaviour of modified atmosphere packages (MAP). The model divided the computational model into four subdomains: a part of the ambient environment, the perforation, the produce layer and the head space above the produce. The model assumed the package walls as rigid and impermeable to gases but heat conduction and the produce layer is treated as a homogeneous porous medium with distributed sink for oxygen and source for carbon dioxide production due to respiration. It presented models of respiration, transpiration, condensation, species transport, gas mixture pressure and velocity and temperature of the produce and gas mixture during MAP of respiring produces. Later the model was solved numerically as a case study and compared to experimental results from literature [51].

Recently, Ho *et al.* [52] developed a two-dimensional multiscale gas exchange model to describe the transport of oxygen and carbon dioxide in conference pear at different spatial scales. The gas exchange of the fruit under CA conditions was described by a macroscale model, whereas for the intracellular gas concentrations of microstructure tissue a microscale model was used. The model was used to evaluate the effect of storage conditions, fruit size and maturity on the intracellular gas concentration. Such multiscale models provide detailed insight in the physiology of fruit during storage under CA conditions at a reasonable computational cost.

Conclusion

This review discussed the different approaches for mathematical modelling of postharvest refrigeration processes; in particular, more attention was given to CFD studies that are used for system design. In most cases the product in consideration was treated as a porous medium and the flow turbulence is solved using two equation turbulence models. With the availability of affordable computer power, more focus should be given to the direct numerical simulation approach. With this method, it possible to get more information about the local flow behaviour and investigate the effects of product geometrical properties, aerodynamic box design and stacking pattern. This direct numerical simulation also can be used to identify turbulence models that could improve the accuracy of porous medium approach. For large scale problems that are difficult to do by a single direct simulation, the use of a multiscale approach could give better information and can be used to develop more accurate porous medium models. Multiscale modelling consists of a range of models at different spatial scales that are linked in such a way that the result of the one scale can be used as input for the model at the other scale. An example is a multiscale model that uses a detailed model of the package on the small scale and a complete room model on the large scale. The small scale model is used to determine the thermodynamic parameters of the product stack that inputs into the large scale model. Such model could be extended with models at even smaller scales (eg, of individual fruits) or at larger scales (eg, a complete cooling plant).

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* A very good article that present a comprehensive mathematical models of respiration, transpiration, condensation, species transport, gas mixture pressure and velocity and temperature of the produce and gas mixture during MAP of respiring produces .

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